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POLICIES AND SUPPORT IN RELATION TO LCA

Indicator selection in life cycle assessment to enable decision making: issues and solutions

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Abstract

Purpose With an ever increasing list of indicators available, life cycle assessment (LCA) practitioners face the challenge of effectively communicating results to decision makers. Simplification of LCA is often limited to an arbitrary selection of indicators, use of single scores by using weighted values or single attribute indicators. These solutions are less attractive to decision makers, since value judgments are introduced or multi-indicator information is lost. Normalization could be a means to narrow the list of indicators by ranking indicators vs. a reference system. This paper shows three different normalization approaches that produce very different ranking of indicators. It is explained how normalization helps maintain a multi-indicator approach while keeping the most relevant indicators, allowing effective decision making.

Methods The approaches are illustrated on a hand dishwashing case study, using ReCiPe as the impact assessment method and taking the European population (year 2000) as the reference situation. Indicators are ranked using midpoint normalization factors, and compared to the ranking from endpoint normalization broken down by midpoint contribution.

Results and discussion Endpoint normalization shows Resources as the most relevant area of protection for this case, closely followed by Human Health and Ecosystem. Broken down by their key driving midpoints, fossil depletion, climate change and, to a lesser extent, particulate matter formation and metal depletion, are most relevant. Midpoint normalization, however, indicates Freshwater Eutrophication, Natural Land Transformation and Toxicity indicators (marine and freshwater ecotoxicity and human toxicity) are most relevant.

Conclusions A three-step approach based on endpoint normalization is recommended to present only the most relevant indicators, allowing more effective decision making instead of communicating all LCA indicators. The selection process breaks out the normalized endpoint results into the most contributing midpoints (relevant indicators) and reports results with midpoint level units. Bias due to lack of data completeness is less of an issue in the endpoint normalization process (compared to midpoint normalization), while midpoint results are less subject to uncertainty (compared to endpoint results). Focusing on the relevant indicators and key contributing unit processes has proven to be effective for non-LCA expert decision makers to understand, use, and communicate complex LCA results.

Keywords Data completeness · Decision making · Hand dishwashing product · Life cycle impact assessment · Multi-indicator · Normalization

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1 Introduction

With an increasing interest in sustainability, life cycle assessment (LCA) is becoming a very popular tool, as

observed by an increased number of users (UNEP/SETAC Life Cycle Initiative 2012), applications and the success of many life cycle management (LCM) conferences around the globe. Programs such as the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC Life Cycle Initiative 2010) have significantly contributed to the success of LCA by creating a forum for further development and harmonization of LCA globally. LCA in Procter & Gamble (P&G), as in many other companies, is applied within a sustainability framework to: (a) understand the potential impacts from products, (b) make environmental improvements, and (c) support environmental claims. In parallel, LCA is taking a much more prominent place in policy tools, as demonstrated by the EU Product and Organization Environmental Footprints (Environmental footprint of products 2012; Environmental footprint of organisations 2012) or the French Grenelle legislation (Ministère de l'Ecologie, du Développement Durable et de l'Energie 2012). Voluntary initiatives like The Sustainability Consortium or TSC (Sustainability Consortium 2012) and the Sustainable Apparel Coalition (Sustainable Apparel Coalition 2012) also rely on LCA to bring stakeholders around the table with the aim of driving sustainable production and consumption.

Although much of the success of LCA can be attributed to its comparative nature and its multi-indicator approach, LCA has a number of issues impacting effective decision making. One of these is the communication of LCA results to guide decision makers who are not LCA practitioners. The continuous and fast development of new impact categories keeps the list of indicators growing, which can make decision making more difficult when there are trade-offs. Several impact assessment methodologies are available such as EPS, CML-IA, EDIP, IMPACT 2002+, Lime, LUCAS, ReCiPe, TRACI (European Commission 2010) each consisting of 10 or more indicators.

There have been several efforts over the years to simplify and improve how LCA is used for decision making. While the earliest impact assessment development was focused on midpoints, further modeling of endpoints (Hofstetter et al. 2000; Steen 1999) aimed to simplify the communication of multiple indicators by aggregating results into three distinct Areas of Protection (AoP): human health, natural ecosystem, and natural resources. Under the umbrella of the UNEP/SETAC Life Cycle Initiative, a framework was developed (Jolliet et al. 2004) to increase the transparency of the overall modeling approach between inventory result, midpoint and endpoint. Newly developed impact assessment suites, such as ReCiPe (Goedkoop et al. 2008), follow this framework. Other simplification approaches looked into aggregation of indicators into a single score by using weighting factors, e.g., Ecological scarcity and EDIP (Frischknecht et al. 2009; Hauschild 2006). However, weighting carries some value choices which can be subjective and thus not desired by most decision makers. The significant complexity of using LCA results in day-to-day practice is further illustrated by the recent success of single attribute indicators, such as Carbon Footprints (ISO 14067 2010; The Greenhouse Gas Protocol 2012; PAS 2050 2011). Development is ongoing for other single indicators such as Water Footprints (ISO/CD 14046 2012; Water Footprint Network 2012) and SETAC is having preliminary discussions on Chemical Footprints. Building on the life cycle thinking concept, the success of these footprints is related to their simple answers, facilitating decision making when comparing alternatives. However, the downside of such footprints is that the multi-indicator approach is abandoned, which may hide increases on other environmental issues not captured in the single footprint. The previous LCA developments and simplification efforts clearly show the importance of minimalism, feasibility, and completeness, which are all important aspects for good decision making.

Normalization is an optional step under ISO 14044 (ISO 14044). LCA results are compared vs. a common benchmark, typically annual resource use and emissions caused by a population in a given region and reference year. Normalization factors for some impact methods (e.g. CML-IA, Ecoindicator 99, Impact 2002+, ReCiPe) use the European population (Laurent et al. 2011a). Bare et al. (2006) developed normalization factors for North America impact models (TRACI). Normalization factors exist for other countries such as the Netherlands (Breedveld et al. 1999) and Australia (Foley and Lant 2009). Some authors developed normalization factors for different geographical scales (Tolle 1997; van Oers and Huppes 2001; Huijbregts et al. 2003; Wegener-Sleeswijk et al. 2008). Normalized results are expressed in person-year or region-year equivalents for a given indicator (midpoint or endpoint). This helps to evaluate if the indicators for the product system under study have high or low contributions relative to the same indicator of the reference system (midpoint or endpoint). Indicators with a relative high contribution can be considered relevant. This is not the same as what a practitioner may perceive as an important indicator, since this is defined by personal or business values. Knowledge about relevant indicators is useful information for a decision maker as it helps to set priorities for different improvement options. Most decision makers will prioritize improvement options in areas with greater relevance, as this could also be used for environmental management systems, sustainability reporting and/or environmental claims. Improvements in less relevant areas could be misleading, which if used for commercial purposes is often called "greenwashing" (Ramus and Montiel 2005).

Normalization however, is also bound with uncertainty, which can be due to lack of data for the reference system or absence of characterization factors (Heijungs et al. 2007; Lautier et al. 2010). In general, inventory completeness is likely to be better for indicators with a global character (e.g. global warming, ozone depletion) than for those with a local character (toxicity). This has been discussed in the updated

EDIP 97 and EDIP 2003 normalization data (Laurent et al. 2011a) and the normalization dataset used for ReCiPe (Wegener-Sleeswijk et al. 2008).

With the latest impact methodologies following the UNEP/SETAC framework for transparent modeling from midpoint to endpoint, the calculation of normalization factors at midpoint and endpoint level has become much more transparent. Most methodologies are developed as midpoint or endpoint methods with the possibility to only normalize at either the midpoint or endpoint. Lime, ReCiPe and Impact 2002+ follow a combined midpoint and endpoint method, which means normalization is possible both at midpoint and endpoint. However, the ranking of normalized indicators can be very different depending on the approach followed. Within the context of decision making, this is highly confusing and must be avoided.

This paper will demonstrate how normalization helps rank indicators and why ranking can be different between endpoint and midpoint normalization. Based on this analysis, an approach to maintain a manageable list of relevant indicators is proposed instead of an arbitrary indicator list or footprint results. This approach is not to make some indicators appear less important (value-based). However, we believe it is helpful to narrow the (sometimes long) list of indicators to three to five indicators, which may help decision making based on a multi-criteria approach (vs. single footprint results), whilst minimizing the number of value choices (vs. single score results). The approach is therefore relevant for LCA application in a business context, as well as for policy development, and is illustrated by a case study on a hand dishwashing product.

2 Methods

The proposed approach is illustrated by the use of a case study on a hand dishwashing product developed by P&G in SimaPro, using ReCiPe v1.07 (Goedkoop et al. 2008) as the impact assessment methodology. The study is a cradle to grave LCA with a functional unit of hand dishwashing 14 plates. The reference flow is 4.5 g of a P&G hand dishwashing product. The system boundaries include the production of raw materials (both for the product as well as its packaging), the mixing of raw materials into a hand dishwashing formula, the packaging making operation, distribution of the packed product, the use of the product by consumers, and the final disposal of the packaging as well as the waste water treatment of the down-the-drain emissions. Primary data include formula and packaging information and specific removal of chemicals in sewage treatment. Secondary data are from ecoinvent v2.2 (2010). For simplification purposes, all sewage is considered to undergo secondary treatment. The geographical scope is Europe.

There exist three approaches to apply normalization in a combined midpoint–endpoint method, which are further discussed in the following sections.

2.1 Endpoint normalization per damage category

The normalized score of product A at the *endpoint* impact category j ($\mathrm{NS}_{A,j}$) is calculated by:

$$\mathrm{NS}_{A,j}^{\mathrm{end}} = \frac{\sum_x \mathrm{CF}_{x,j}^{\mathrm{end}} \times M_{A,x}}{\sum_x \mathrm{CF}_{x,j}^{\mathrm{end}} \times M_{\mathrm{NR},x}} \tag{1}$$

where the numerator is calculated by multiplying the characterization factor of each Life Cycle Inventory (LCI) flow x in the endpoint impact category j ($\mathrm{CF}_{x,j}{}^{\mathrm{end}}$)by the amount of LCI flow x in product A for the functional unit defined ($M_{A,x}$), and the denominator is calculated by multiplying the characterization factor of each LCI flow x in the endpoint impact category j ($\mathrm{CF}_{x,j}{}^{\mathrm{end}}$) by the amount of LCI flow x in the normalization reference $M_{\mathrm{NR,x}}$. The denominator is also known as the endpoint normalization factor of damage category j ($\mathrm{NF}_j{}^{\mathrm{end}}$).

2.2 Midpoint normalization per midpoint

The normalized score of product A at the *midpoint* impact category i ($\mathrm{NS}_{A,i}$) is calculated by:

$$\mathrm{NS}_{A,i}^{\mathrm{mid}} = \frac{\sum_x \mathrm{CF}_{x,i}^{\mathrm{mid}} \times M_{A,x}}{\sum_x \mathrm{CF}_{x,i}^{\mathrm{mid}} \times M_{\mathrm{NR},x}} \tag{2}$$

where the numerator is calculated by multiplying the characterization factor of each LCI flow x in the midpoint impact category i ($\mathrm{CF}_{x,i}{}^{\mathrm{mid}}$) by the amount of LCI flow x in product A for the functional unit defined ($M_{A,x}$), and the denominator is calculated by multiplying the characterization factor of each LCI flow x in the midpoint impact category i ($\mathrm{CF}_{x,i}{}^{\mathrm{mid}}$) by the amount of LCI flow x in the normalization reference $M_{\mathrm{NR},x}$. The denominator is also known as the midpoint normalization factor of impact category i ($\mathrm{NF}_i{}^{\mathrm{mid}}$).

2.3 Endpoint normalization with relative contribution of normalized midpoint

The normalized score of product A at the *endpoint* impact category j specified per midpoint impact category ($\mathrm{NS}_{A,i,j}{}^{\mathrm{end}}$) is calculated by:

$$NS_{A,i,j}^{end} = \frac{\sum_x CF_{x,i,j}^{end} \times M_{A,x}}{\sum_x CF_{x,j}^{end} \times M_{NR,x}} \tag{3}$$

Where the numerator is calculated by multiplying the characterization factor of the LCI flow x in the endpoint

impact category j specified for the midpoint impact category i ($CF_{x,i,j}^{end}$) by the amount of LCI flow x in product A for the functional unit defined ($M_{A,x}$), and the denominator is calculated by multiplying the characterization factor of each LCI flow x in the endpoint impact category j ($CF_{x,j}^{end}$) by the amount of LCI flow x in the normalization reference $M_{NR,x}$. The denominator is also known as the endpoint normalization factor of damage category j (NF_j^{end}).

This third option gives a very different view of the normalized result, and strictly speaking it should not be called normalization, but a specific form of contribution analysis; it does not specify the contribution of an impact category to the overall environmental load, but to the endpoint to which it is linked.

The case study results are normalized at midpoint and endpoint, using the hierarchist perspective and using the European population for the reference year 2000. The selection of the hierarchist perspective is a value-based decision which has implications on how midpoints connect to endpoints. However, the hierarchist perspective is the most commonly used cultural perspective (Goedkoop et al. 2008), for which reason it was used in this study. When the endpoint method is used, the software uses endpoint normalization factors, but displays the results either by area of protection ($NS_{A,j}^{end}$) (Eq. (1)) or by midpoint contribution within endpoints ($NS_{A,i,j}^{end}$) (Eq. (3)). All 18 midpoints in ReCiPe have a single connection to one of the three AoPs, with exception of Climate Change, Marine Eutrophication and Water Depletion (Fig. 1). The last two midpoints are currently not further modeled into endpoints, while the first one connects both to human and ecosystem health. Also, there are no data in the reference set for Water use flows, which excludes this indicator from the normalization process. With this third option, it is possible to compare the ranking of normalized indicators using the midpoint normalization and the endpoint normalization broken down by their midpoint contribution. For impact assessment methodologies not following the UNEP/SETAC framework for transparent modeling from midpoint to endpoint, normalization is only possible at either midpoint or endpoint (i.e., only the first two approaches are possible).

3 Results

Results for each indicator relative to the total indicator score across all life cycle stages are given in Table 1. As can be seen, the contribution of the Use stage (i.e., water heating) is

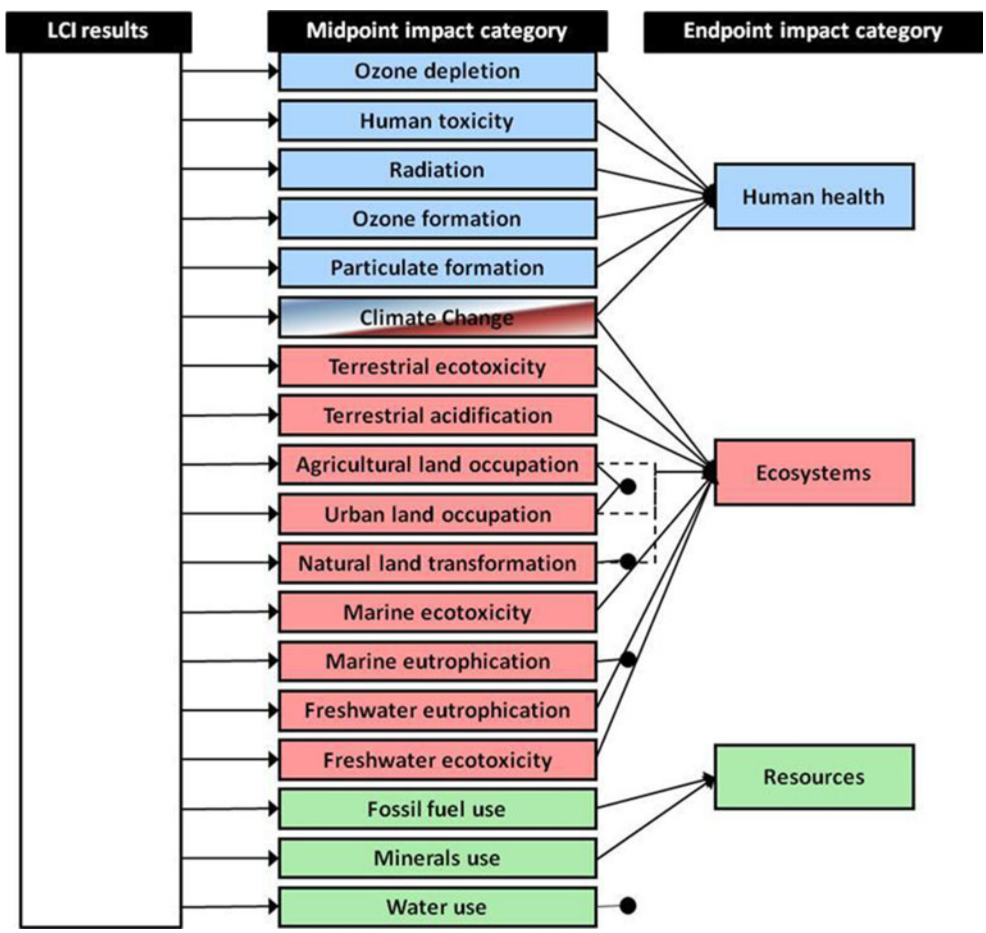


Fig. 1 Simplified illustration of the ReCiPe method and respective impact pathway and relationship between midpoints and endpoints. Marine eutrophication and Water use are not assessed at endpoint level (*dots*); Agricultural and land occupation and natural land transformation do not have a midpoint to endpoint relation so endpoint assessment is directly linked to LCI results (*dashed lines*)

Table 1 Characterized midpoint results for 1 use of hand dishwashing product at midpoint level using ReCiPe v1.07. Results are displayed for each indicator in percentage relative to the total indicator scores across all life cycle stages

Midpoint Indicator	Raw materials	Formulation	Packaging	Distribution	Use	End of Life
Climate change	3	<1	1	<1	96	<1
Ozone depletion	2	<1	<1	1	97	<1
Human toxicity	2	1	1	<1	96	<1
Photochemical oxidant formation	9	<1	1	1	89	<1
Particulate matter formation	6	1	1	1	92	<1
Ionizing radiation	1	1	<1	<1	97	<1
Terrestrial acidification	6	1	1	<1	92	<1
Freshwater eutrophication	2	1	<1	<1	97	<1
Marine eutrophication	44	<1	1	<1	54	<1
Terrestrial ecotoxicity	4	<1	1	1	94	<1
Freshwater ecotoxicity	2	1	1	<1	97	<1
Marine ecotoxicity	2	1	1	<1	96	<1
Agricultural land occupation	5	<1	4	<1	90	<1
Urban land occupation	3	<1	1	1	94	<1
Natural land transformation	2	<1	<1	1	96	<1
Water depletion	<1	<1	<1	<1	100	<1
Metal depletion	7	<1	1	1	91	<1
Fossil depletion	5	<1	1	<1	93	<1

the key driver behind all indicators. In the following sections, normalized results are analyzed by the 3 different normalization methods presented in the previous section.

3.1 Endpoint normalization per damage category

Normalizing at endpoint (Fig. 2) shows Resources as being the most relevant AoP, but the Human Health and Ecosystems AoPs follow within factors of 2 and 4, respectively. While this normalization shows only three indicators and without uncertainty information, it is difficult to turn this into focused action, since results hide the underlying mechanistic effects. This approach could be perceived by decision makers as having to make value choices for making improvements in Resources vs. Human or Ecosystem Health AoP, and contains insufficient detail about what exactly to improve (e.g., in Resources). In fact, improvement options often have effects in different AoPs, as will be discussed later, which is not transparently shown in this presentation of results.

3.2 Midpoint normalization

Using the midpoint approach for the hand dishwashing case study (Fig. 3), Freshwater eutrophication, toxicity indicators

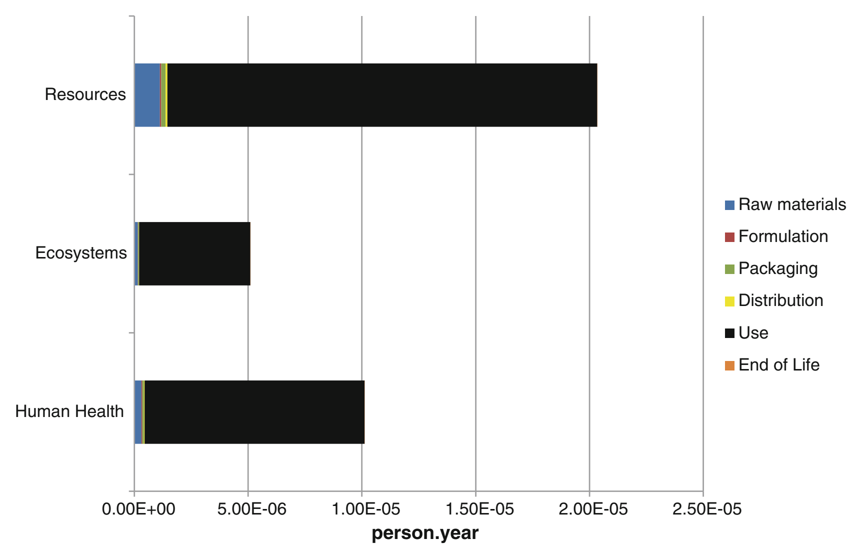


Fig. 2 Normalized endpoint results per damage category (European population, year 2000) for 1 use of hand dishwashing product using ReCiPe v1.07

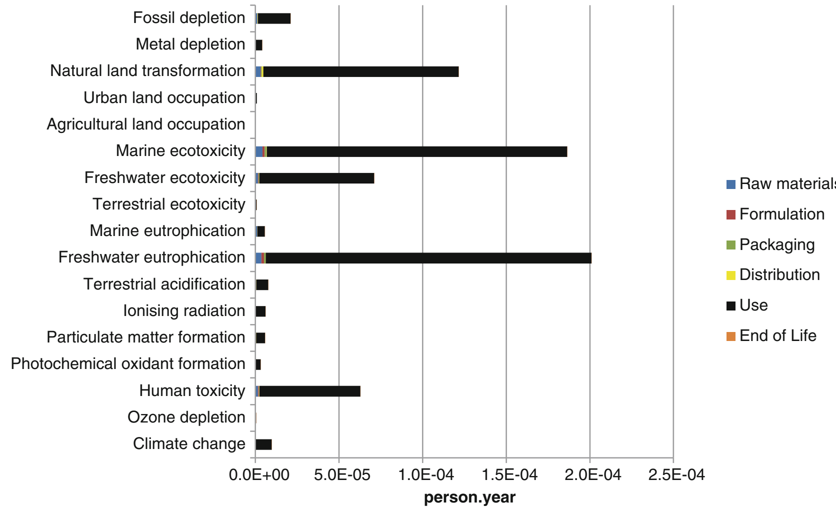


Fig. 3 Normalized midpoint results per midpoint (global population, year 2000) for 1 use of hand dishwashing product using ReCiPe v1.07

(Marine and Freshwater Ecotoxicity and Human toxicity) and Natural land transformation are shown to be the most relevant. Fossil depletion, Climate Change, Terrestrial acidification, Ionizing radiation, Particulate matter formation, Metal depletion and Photochemical oxidant formation follow the ranking, but are one order of magnitude lower. The driving emissions and contributing processes for these top indicators are presented in Table 2. Note that the Human toxicity indicator is totally independent of the product composition and relates to electricity use for heating water during the use stage.

Human toxicity is an indicator that is often confusing to decision makers more familiar with risk assessment (as required in various pieces of legislation). For this case study, the human risk assessment, supported by long term monitoring data, concludes that the product is safe. The assessment is primarily based on skin exposure during product use, which is very different from the exposure scenarios (inhalation and ingestion) in the LCIA method. Metals from electricity production and their behavior in waste disposal are the key driving processes, thus not at all specific to the product under study. This example clearly demonstrates that the use of normalized LCIA toxicity indicators for the purpose of safety evaluation of products can be highly misleading.

No freshwater toxicity characterization factors could be calculated for down-the-drain emissions from used hand dishwashing product using the ReCiPe method. This is because toxicity indicators in ReCiPe are based on USES-LCA 2.0 (van Zelm et al. 2009), for which a limited list of characterization factors is available. A simple Excel tool is not available for the calculation of missing characterization factors in the inventory list. Since such a calculation tool exists for USEtox (Rosenbaum et al. 2008), freshwater toxicity results were recalculated using this method. The analysis shows that waterborne emissions after sewage treatment are the key driver behind this indicator (Fig. 4). Similar to the human toxicity explanation above, P&G ecotoxicologists conduct environmental risk assessments (ERA) and monitoring of individual ingredients in hand dishwashing products and ensure they are safe for the environment prior to the product being sold (HERA initiative

Table 2 Contributing emissions and processes to the highest normalized results at the midpoint and endpoint level, using ReCiPe v1.07

	Impact category	Driving emissions	Contributing processes
Midpoint	Marine ecotoxicity Freshwater ecotoxicity	Ni, Mn, Zn, V, Co	Waste handling in electricity production system
	Freshwater eutrophication	Phosphate	
	Human toxicity	Mn, As, Se	
	Natural land transformation	Transformation from sea and ocean	Off-shore natural gas production
Endpoint	Fossil depletion Climate change	Natural gas, coal (hard/brown), crude oil CO_2, CH_4	Electricity from the grid
	Human toxicity	Mn, As, Se	Waste handling in electricity production system
	Particulate matter	SO*x*, NO*x*, PM2.5, PM10	Electricity from the grid
	Metal depletion	Cu, Fe, Ni	Distribution of electricity and steel production transport vehicles

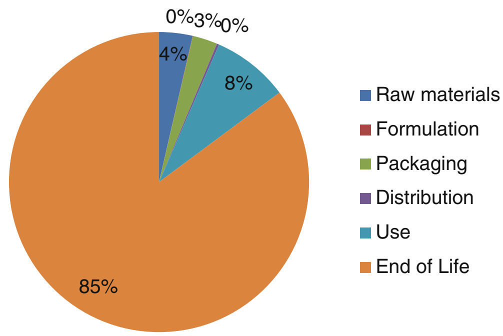


Fig. 4 Life cycle stage contribution to Freshwater aquatic ecotoxicity using USEtox for 1 use of hand dishwashing product

2012; AISE Charter for Sustainable Cleaning 2012; REACH regulation 2006). ERA and LCA tools are complementary. LCA is helpful to flag that freshwater toxicity could present a potential impact (hazard). The ERA goes further to evaluate if the exposure threshold is exceeded, thereby being more spatially explicit and taking into account other emission sources than what is defined by the functional unit in the LCA study.

3.3 Contribution of midpoints in the endpoint normalization

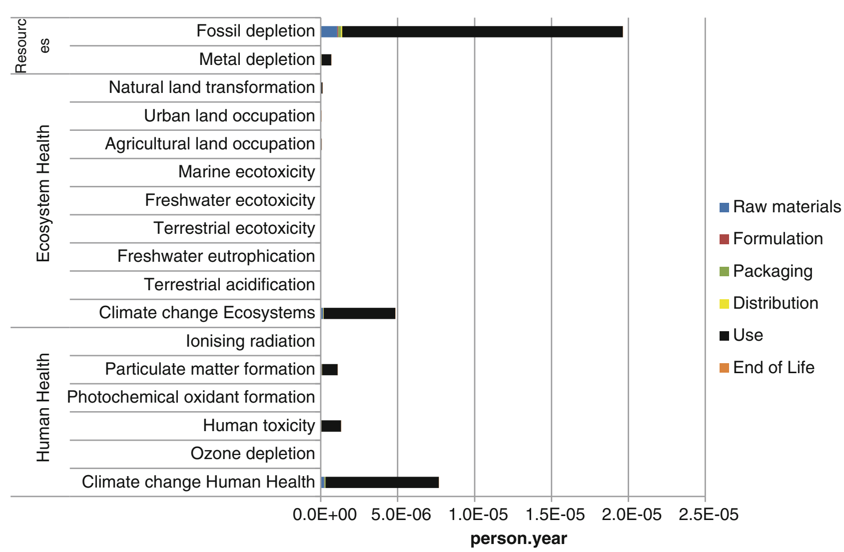
The endpoint normalization approach reported per midpoint impact category (Fig. 5) shows Fossil depletion and Climate Change as the most relevant indicators, followed by particulate matter formation, human toxicity and metal depletion. All other indicators are 2 or more orders of magnitude lower. The driving emissions and their contributing processes for the indicators with high normalized results are presented in Table 2. Compared to the normalization at endpoint (Eq. (1)), the benefit of this approach comes from it showing how much different midpoints contribute within the overall AoPs. While endpoint normalization broken down by their midpoint contribution shows Fossil depletion and Climate change as most relevant for this system, these indicators rank fifth when normalized at the midpoint, an order of magnitude lower than the toxicity indicators. Note that the contribution from midpoints into endpoints is identical for characterized and normalized results (Electronic Supplementary Material, Tables SI1 and SI2). It is important to correctly interpret normalized midpoint and endpoint results, which is discussed in the next section.

4 Discussion

4.1 Interpretation of normalized results

The interpretation of normalized results at the midpoint and endpoint level provides different insights. Normalized midpoint results compare for each individual midpoint the result vs. the reference system. It therefore gives insight into the system's contribution to that indicator. Systems with relative high contributions suggest that these are hotspot systems with improvements leading to overall considerable reduction potential for that indicator. It should be recognized that the absolute value is dependent on the magnitude of the functional unit of the system and subject to uncertainty. First, the absolute value of the normalized score depends on the chosen functional unit. In our reference study, the cleaning of 14 plates was chosen. This number is compared to the reference, in our case the annual emissions and resource use from the European population (year 2000). Should we have chosen as functional unit the annual use of a dishwashing product by the entire European population, the absolute values would be much larger, but the indicator ranking would not change (only scale effect). Second, since normalization factors are subject to uncertainty (see

Fig. 5 Normalized results (European population, year 2000) for 1 use of hand dishwashing product at endpoint level using ReCiPe v1.07. Endpoint results are broken down by their contributions at the midpoint level and by life cycle stage contribution



Section 4.3), normalized LCA results are also subject to uncertainty. Without more information on uncertainty ranges, it is impossible to evaluate if the normalized result is significantly different from the chosen threshold. For example, if a threshold was selected of 10^{-5} person-year, uncertainty information is necessary in Fig. 5 to understand if fossil depletion and climate change human health/ecosystems would exceed the threshold. In comparative LCAs, the magnitude of the functional unit does not change the comparison in a relative way, but setting a threshold for normalized results to define if a given indicator is relevant is still subject to the magnitude of the functional unit for all comparisons in the study.

Normalized endpoint results, evaluated by their midpoint contribution, provide a different interpretation. Indicators with high contribution within a given endpoint suggest that the system has a high relative contribution in an AoP. In other words, this places the characterized results in perspective with what we want to safeguard. In our case study, climate change is the highest contributing midpoint within the human health endpoint. This means that even if the potential climate change impact of hand dishwashing is small compared to the potential climate change impact of the reference system (midpoint normalized score), its contribution is large when analyzing the human health endpoint, because climate change has a high contribution in the human health indicator of the reference system. To better understand the different interpretation between normalization approaches at midpoint and endpoint, it is important to take a closer look at how midpoints and endpoints are calculated.

4.2 Midpoint contribution in endpoints

Figure 6 depicts how elementary flows from the inventory table are linked to midpoint and endpoint indicators in LCIA. The contribution of each flow into the final indicator value is established by assigning a characterization factor (ChF). When midpoints are further modeled to endpoints, the contribution of a selected midpoint into the final endpoint score is again characterized. Therefore, this process involves three sets of ChFs with the inventory to endpoint ChF (ChF3) being the product of the inventory to midpoint ChF (ChF1) and midpoint to endpoint ChF (ChF2). Since ChF1 and

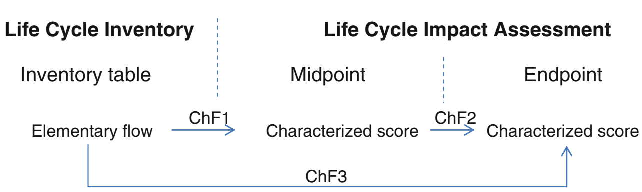


Fig. 6 Characterization factors in the modeling of impact indicators from data from an inventory table

ChF3 provide the direct relationship between the inventory table and the impact assessment results for midpoints and endpoints respectively, they are the most important to work with from a practitioners' perspective.

The analysis of the characterization of individual midpoints to an endpoint (ChF2) provides a lot of insight into the different ranking discussed above (Fig. 7). Note the logarithmic scale. Within the human health AoP, ChF2 is highest for ozone depletion (ODL/ODH) and particulate matter formation (PMF), with other contributing midpoints 2 or more orders of magnitude lower. Within the ecosystem health AoP, ChF2 is highest for land transformation (NLTH/NLTL), followed by land occupation (agricultural and urban) by 2 orders of magnitude. All other contributing midpoints are 9 orders of magnitude smaller than land transformation. The interpretation of the magnitude of ChF2 depends on where a midpoint is in the entire cause effect modeling pathway for a given endpoint. As such, interpretation of ChF2 should be in combination with the midpoint characterized result. This difference in ChF2 is important for the normalization factors' sensitivity to data completeness, as discussed in the next section.

4.3 Issues with normalization

Although normalization provides insight into the relevance of indicators for a system, the normalization process requires the use of data, which may introduce uncertainty that should be accounted for in the ranking of indicators when used for decision making. Normalization factors are calculated from characterized results of a reference dataset. The quality of the reference data set, and therefore of the normalization factors, depends on two elements: data completeness of the reference set and impact assessment model completeness and uncertainty.

First, for midpoints with a lot of contributing elementary flows (e.g. toxicity indicators), data completeness can be expected to be different due to differences in data collection at unit process vs. regional level. This difference in scale plays an important role in the normalization of LCA results. Figure 8 shows the distribution of the 758 characterized elementary flows used in the normalization reference, with 5 % (36) assigned as resource flows (incl. land occupation or transformation flows), 34 % (257) airborne emissions, 26 % (200) waterborne emissions and 35 % (265) emissions to soil. Although the toxicity indicators include between 400 and 600 elementary flows from different environmental compartments, this is only a fraction of the tens of thousands of chemicals currently being used in commerce; contributing data are far from complete for this indicator (Heijungs et al. 2007; Laurent et al. 2011b). Another example of data incompleteness from scale differences is the presence of trace metals in fossil fuels, which are not recorded in the

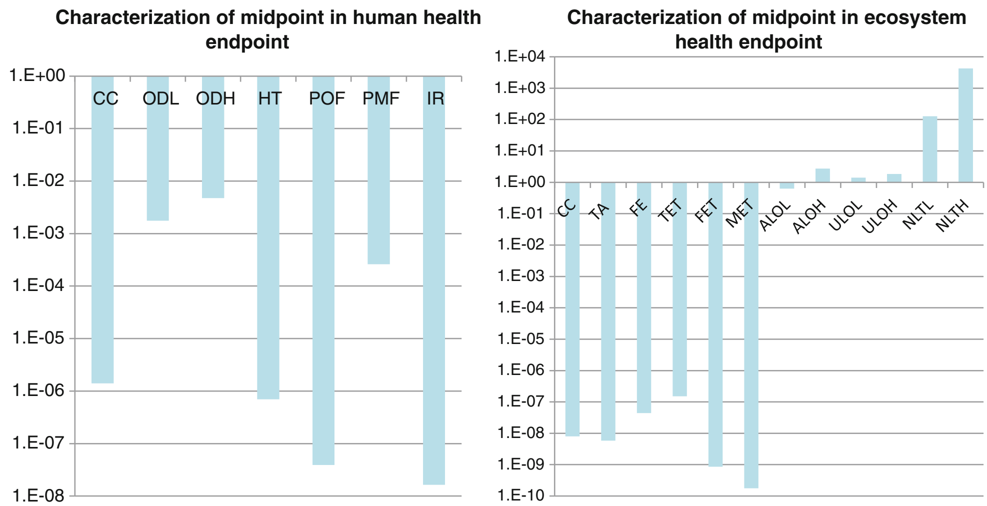


Fig. 7 Characterization of midpoints to endpoints for human and ecosystem health in ReCiPe. *CC* Climate change, *ODL/ODH* Ozone depletion low/high (characterization dependent on elementary flow), *HT* Human toxicity, *POF* Photochemical oxidant formation, *PMF* Particulate matter formation, *IR* Ionizing radiation, *TA* Terrestrial acidification, *FE* Freshwater eutrophication, *TET* Terrestrial ecotoxicity, *MET* Marine ecotoxicity, *ALOL/H* Agricultural land occupation low/high (characterization dependent on elementary flow), *ULOL/H* Urban land occupation low/high (characterization dependent on elementary flow), *NLTL/H* Natural land transformation low/high (characterization dependent on elementary flow)

statistics being used for the reference system, but sometimes are part of unit process databases. Frequently used life cycle inventory databases, such as ecoinvent (Ecoinvent v2.2 2010), do include these trace metals creating a discrepancy for toxicity indicators between the system under study and the reference system. By contrast, for midpoints with only a few contributing elementary flows (e.g. fossil depletion) or well known environmental issues (e.g. climate change, ozone depletion or particulate matter), scale differences are less important.

Second, while emission data may exist for some elementary flows, ChFs may not be available or of poor quality due to lack of supporting input data for their underlying models. This leads to incompleteness in both the system under study as well as the reference system.

Due to the aforementioned issues, the normalization step generally introduces some uncertainty. Notably, the introduced uncertainty is different for midpoint and endpoint normalized results. Because some midpoints contribute less within a given AoP, the bias from data incompleteness has a lower impact at the endpoint level. Table 3 provides an overview of the various midpoint indicators' contribution from the reference system into each of the three AoPs. Within the Human health AoP, Climate change (78 %) and Particulate matter formation (19 %) are the key driving midpoints. For the ecosystem health AoP, these are

Fig. 8 Number of contributing elementary flows in the European 2000 normalization reference set for the different ReCiPe midpoints

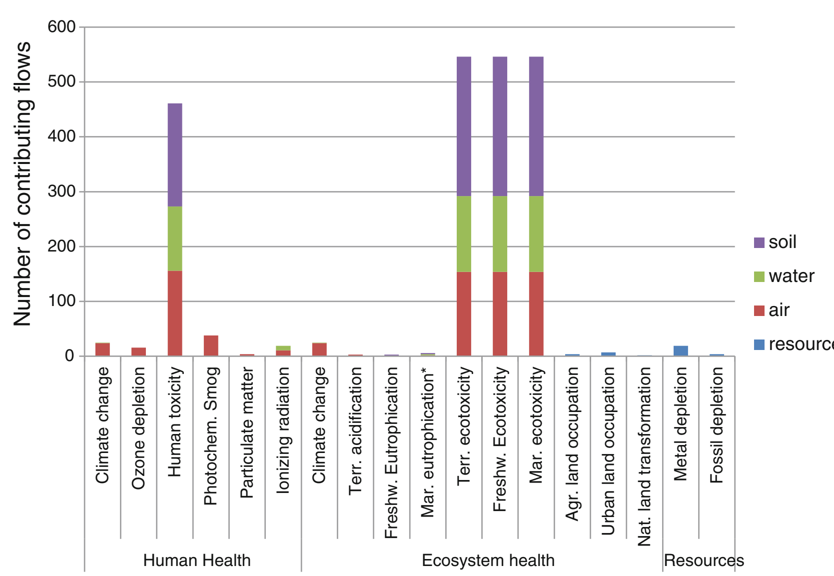


Table 3 Contribution of midpoint indicators within the three endpoints for the reference system (European population in year 2000) calculated with SimaPro 7.3.3. and ReCiPe v1.07

Endpoint	Contributing midpoint	Unit	Endpoint result	Contribution within AoP (%)
Human health	Climate change Human Health	DALY	1.57E−02	78
	Ozone depletion	DALY	6.86E−05	<1
	Human toxicity	DALY	4.14E−04	2
	Photochemical oxidant formation	DALY	2.07E−06	<1
	Particulate matter formation	DALY	3.87E−03	19
	Ionizing radiation	DALY	1.03E−04	1
Ecosystems	Climate change Ecosystems	species-year	8.89E−05	49
	Terrestrial acidification	species-year	1.99E−07	<1
	Freshwater eutrophication	species-year	1.84E−08	<1
	Terrestrial ecotoxicity	species-year	1.24E−06	1
	Freshwater ecotoxicity	species-year	9.38E−09	<1
	Marine ecotoxicity	species-year	1.50E−09	<1
	Agricultural land occupation	species-year	8.17E−05	45
	Urban land occupation	species-year	8.42E−06	5
	Natural land transformation	species-year	2.98E−07	<1
Resources	Metal depletion	$	5.10E+01	17
	Fossil depletion	$	2.57E+02	83

Climate change (49 %) and Agricultural land occupation (45 %). Nevertheless, as stated in Section 4.4.3.2.1 of ISO 14044 (2006), "normalization may be helpful for providing and communicating information on the relative significance of the indicator results".

4.4 Why is endpoint normalization preferable to rank indicators?

When LCA results are normalized at midpoint, the ranking of indicators assumes a similar level of data completeness for each midpoint. As mentioned before, this is not the case. Also, the issue of data (in)completeness exists for each midpoint, but each midpoint's contribution to the endpoint result differs. That means that endpoints are less sensitive to data completeness for midpoints that have low contribution in that endpoint. This explains why toxicity indicators rank high when normalized at midpoint, but have a low contribution in the endpoint.

Therefore, normalization by endpoints seems the more preferable approach. Further, breaking down the different endpoints into their major driving midpoints is strongly recommended, in order to better understand where improvements should be focused and which midpoint they are addressing. When normalized endpoint results, split into their midpoint contribution (Eq. 3), are used to rank indicators, no value judgment between the three AoPs is implied. To make this more obvious, it may be helpful to display results as in Fig. 9 for decision makers to recognize the top 3–5 indicators and relationships. In practice, Fossil depletion (resources AoP), Climate change (both Human and Ecosystem health AoP) and Particulate matter (human health AoP) midpoints strongly correlate as they all depend on the use of energy across the value chain. Therefore, improvements in one AoP will normally result into related improvements in other AoPs.

The previously discussed issue of data completeness for some normalization approaches, as well as a good understanding of the contributing emissions and processes, is important when ranking indicators for their environmental relevance.

A recent LCA study on surface cleaners using the ReCiPe method (Kapur et al. 2012) concluded that human toxicity, freshwater and marine ecotoxicity were "leading impact

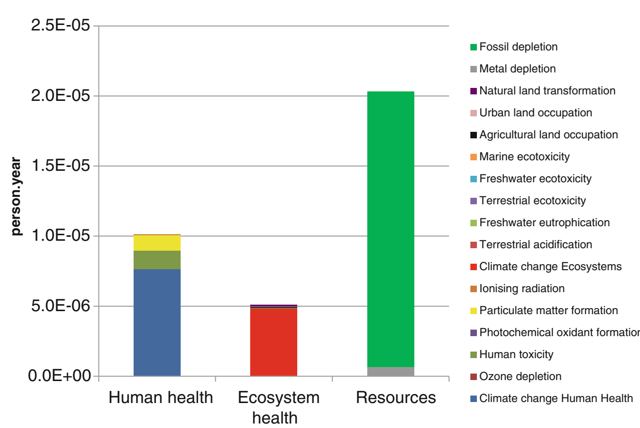


Fig. 9 Normalized results (European population, year 2000) for 1 use of hand dishwashing product at endpoint level using ReCiPe v1.07. Endpoint results are broken down by their midpoint contribution

categories", since they appeared to be dominant after normalization at the midpoint level. These indicators were mainly driven by the production of raw materials (mostly surfactants) and are thus very comparable to hand dishwashing detergents. In our study, these indicators rank also high when normalized at the midpoint level (Table SI3, Electronic Supplementary Material), but this is explained by data incompleteness bias of the reference system. Furthermore, this study shows that these midpoint indicators have a minor contribution in the ecosystem AoP. It could be therefore misleading to call these leading indicators based on normalized midpoint results.

Another reason to select endpoint normalization is that ranking is less dependent on the choice of reference system. Lautier et al. (2010) conclude that at the midpoint level, normalized results may differ depending on the choice of regional reference set. In our case study, freshwater eutrophication and natural land transformation midpoints rank as the two most relevant indicators when the European population is used as the reference set (Table SI3, Electronic Supplementary Material). However, if the global population is selected as the reference, then human toxicity and marine ecotoxicity are the most relevant indicators. Freshwater eutrophication ranks 4th and natural land transformation ranks 13th! At the endpoint level however, there is much more consistency between the two different reference systems (Electronic Supplementary Material, Table SI4), since the global reference data set is extrapolated from the European one. For this hand dishwashing case study, the selection of a global reference may be preferred as there is a global supply chain. On the other hand, since the majority of the emissions are driven by the use phase, occurring in Europe, one may consider this to be more important. Heijungs et al. (2007) suggest to use global population if emissions occur outside the reference system, however, due to data availability issues or inconsistencies in data collection between different regions, it is difficult to produce reliable global data and often extrapolations are necessary (Wegener-Sleeswijk and Heijungs 2010). If normalization is used to rank indicators, a sensitivity analysis with different reference systems is therefore recommended.

4.5 Ranking indicators to guide decision making

LCA is an important tool within a sustainability framework, because it is a multi-indicator approach and is relative in nature, allowing the comparison of different improvement options. On the other hand, decision making is made easier when results are presented in a way that is focused on environmentally relevant information, using objective criteria to the extent possible. Because there are no means to scientifically define if an LCA indicator is close at or exceeds a threshold, it is impossible to understand its importance and therefore the discussion about important indicators becomes a value-based discussion. Normalizing LCA results helps to rank indicators relative to a given existing situation. Therefore, even when indicators are ranked, the fact that a selection is made based on this ranking implies a value choice (usually by assuming they are equally important). Nevertheless, it is judged to be preferable as it starts from the assumption that decision makers strive to improve vs. the reference and focus on indicators with high contribution.

From the previous discussion, we propose to present LCA results to non-LCA experts following a three-step approach. First, rank indicators by normalizing LCIA results at the endpoint level and break them out by midpoint contribution. From this ranking process, report only the most relevant indicators. Typically, this allows narrowing a list of 18 indicators to three to five indicators (as demonstrated in this case study). It is useful to evaluate if contributing emissions and processes are within the practitioner's control to ensure focused action is feasible. Second, report these indicators using midpoint units. It is often argued that endpoints simplify the understanding of impact assessment results, as they focus on the AoP. Our own experience is different. The use of odd units, such as DALYs (disability adjusted life years) or Potentially Disappeared Fraction of species square meter year creates more confusion when talking climate change to business managers than kilograms CO_2-eq and distracts the discussion from what really matters. In addition, the uncertainty on midpoint results is smaller compared to those at endpoint level, because the overall uncertainty is driven by individual parameter uncertainty, which is larger for endpoints than for midpoints as more parameters are used in the modeling. Third, other indicators may be added, depending on the goal and scope of the study. Currently, there are no Water depletion normalization data. If water is considered important within the system under study (e.g., irrigation water for crop production), it may be included in the final list of indicators. In addition to reporting relevant indicators, other life cycle thinking based indicators such as Cumulative energy demand, Non-renewable energy and/or total Solid waste treated can be added. Energy relates strongly to many LCA indicators (Huijbregts et al. 2012) which helps in making a comprehensive evaluation. Furthermore, water, energy and solid waste from manufacturing are often used in sustainability reporting or environmental management systems and links the business case to systems that corporations are used to working with. Sometimes, indicators with some known issues for a given product category may also be added. For example, Freshwater eutrophication is included when assessing products from renewable materials, related to fertilizer use. In all of these cases, value-based decisions cannot be avoided, but are kept to a minimum and can be justified.

4.6 Improvement options for hand dishwashing products

In view of facilitating decision making with LCA indicators, a number of approaches were listed in the introduction section. Single footprints would not be considered if a multi-indicator approach is the basis for decision making. If decision making is based on objective criteria, weighting (single scores) is not possible. Normalization vs. a reference system could be a solution to rank indicators and make decisions on the indicators with high ranking. As shown in the previous sections, the ranking of the most relevant indicators is different between midpoint and endpoint normalization. If product comparison or improvement options would be based on midpoint normalization, freshwater eutrophication and marine ecotoxicity would be selected as the basis for decision making. This could lead to situations where products are claimed to be preferable or improved on an environmental attribute which is not meaningful or which is largely overestimated. This is not a sound basis for making claims or communicating benefits/attributes to third parties. If endpoint normalization is selected, fossil fuel and climate change would be those with highest ranking and are shown in Fig. 9 to have major contributions in three different AoPs. Fossil and metal depletion and climate change are all related to the heating of water during the use stage. Innovations that lead to products with better performance at low temperature, or saving water use, are therefore expected to lead to meaningful improvements. Products that lead to changing consumer behavior toward saving water or lower water temperature are a second improvement option. Sourcing hand dishwashing raw materials that are less dependent on fossil resources is a third improvement option, but with a lower improvement potential (as shown in Table 1).

5 Conclusions

LCA is a useful tool within a sustainability framework, thanks to its multi-indicator approach and comparative nature. However, decision making is not simple with an ever increasing list of indicators. If decision makers follow a multi-criteria approach based on life cycle thinking, results may be normalized vs. a reference system to rank LCA indicators. This approach keeps a good balance between a multi-criteria approach, whilst still keeping the list of indicators manageable. Ranking of indicators however is different when normalization is done at the midpoint or endpoint level, broken down by their midpoint contribution. The underlying reasons behind this different ranking are explained. Due to various data availability and completeness issues with midpoint normalization and lower dependence on the choice of the reference system, endpoint normalization broken down by their midpoint contribution is proposed to rank indicators according to their relevance.

The approach is applied on a hand dishwashing case study, using ReCiPe v1.07 as the impact assessment method and taking the European population as a reference system. The study concludes that the most relevant indicators for a hand dishwashing product are fossil fuel depletion, climate change, particulate matter and metal depletion. Using these indicators, a number of improvement opportunities for the product category are listed. With this approach, product comparison by use of LCA is focused on a manageable number of relevant indicators, which is considered a sound basis for decision making and communication of results to third parties.

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